Regularities in galaxy spectra and the nature of the Hubble sequence

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Abstract. We have investigated some statistical properties of integrated spectra of galaxies with principal component analysis. The projection of the spectra onto the plane defined by the first two principal components shows that normal galaxies are in a quasi-linear sequence that we call spectral sequence and is closely related to the Hubble morphological sequence. We verify that the spectral sequence is also an evolutive sequence, with galaxy spectra evolving from later to earlier spectral types. Considering the close correspondence between the spectral and morphological sequences, we speculate that galaxies may evolve morphologically along the Hubble sequence, from Sm/Im to E. If this is the case, the first galaxies were mainly gas rich irregular objects, which evolved later along the morphological sequence as long as mergers and interactions increased their masses and developed their spheroidal components.

1. Introduction

We present a study of Kennicutt's (1992a,b) spectrophotometric atlas, looking for global regularities in the integrated spectra of galaxies. This is done with a standard statistical technique, Principal Component Analysis (PCA). Similar analysis, dealing mainly with spectral classification, are presented by Connolly et al. (1995) and Folkes, Lahav & Maddox (1996).

Kennicutt's atlas contains 55 integrated spectra. We consider here a subsample with 23 normal galaxies. This set covers the Hubble sequence from E to Im, avoiding objects with any evidence of peculiarity (e.g. AGNs, starbursts, mergers). Although small, the sample discussed here allows us to explore the connection between normal galaxy spectra and morphology. An analysis of all spectra is presented elsewhere (Sodré & Cuevas 1996).

2. Principal Component Analysis

Suppose we have a sample of N integrated spectra, all covering the same rest-frame wavelength range (3750 - 6500 Å). Each spectrum is described by a M-dimensional vector containing the galaxy flux at M uniformly sampled wavelengths (here M=1300). Let $\mathcal{S}$ be the M-dimensional space spanned by these 'spectral' vectors. An integrated spectrum, then, is a point in the $\mathcal{S}$-space. Here we apply PCA to find a suitable plane in $\mathcal{S}$, defined by the two first principal

components of the data, y_1 and y_2. We call it the *principal plane*, because it is the plane that contains most of the variance in the spectral space.

We apply PCA to the covariance matrix of the data, and with spectra normalized in mean flux, $\sum_\lambda f_\lambda = 1$. The total variance contained in the principal plane is then 93%. We show elsewhere (Sodré & Cuevas 1996) that our main results do not depend on data normalization or whether one applies PCA to the covariance or to the correlation matrix of the data.

3. The spectral sequence

Figure 1a shows the projection of the 23 spectra onto their principal plane. The projected spectra of almost all galaxies are arranged along a quasi-linear sequence which we call *spectral sequence*. The few outliers are Sc and Sm/Im galaxies with spectra dominated by nebular emission lines. We also show in figure 1a the projections of the mean spectra binned in 5 morphological groups: E, S0, Sa-Sbc, and Sc-Im. They preserve, over the spectral sequence, the same ranking of the Hubble morphological sequence. We conclude that *the spectral sequence correlates strongly with the Hubble morphological sequence* (see also Sodré & Cuevas 1994; Connolly et al. 1995; Folkes, Lahav & Maddox 1996). Note that the spectral sequence provides quantitative support for a one-dimensional description of the general properties of normal galaxies, like the Hubble morphological sequence. It also indicates that there is not a dividing line in global spectral properties between elliptical and spiral galaxies, and that lenticulars have spectra intermediate between those two morphological groups.

The very existence of the spectral sequence, and its correlation with the Hubble sequence, indicates that one single parameter may be responsible for the integrated spectra of normal galaxies- and of the morphological sequence. For instance, Gallagher, Hunter & Tutukov (1984), Sandage (1986) and Ferrini & Galli (1988), suggest that several properties of the Hubble sequence can be explained by variations in the star formation rate of galaxies.

We have investigated this hypothesis with Bruzual & Charlot (1995, hereafter B&C) revised models of spectral evolution of galaxies. We have only considered models with a single parameter, the characteristic star formation time-scale of a galaxy, τ. In figure 1b we show, for several values of τ, the projection of the model spectra onto the principal plane defined by the 23 galaxies in our set of normal galaxies. The model spectra overlap partially the spectral sequence for all but the latest types. For these galaxies, emission lines associated to ongoing star formation dominate the spectra.

We plot in figure 1c the evolutive track for the $\tau = 0$ model, with galaxy ages running from 0 to 20 Gyr. The evolutive track of an instantaneous burst overlaps most of the spectral sequence, that is, its spectrum evolves from late to early-types along the sequence. For the constant star formation rate model ($\tau = \infty$), the evolutive track overlaps the $\tau = 0$ one, but in this case the oldest spectrum falls near the centroid of normal Sc galaxies. Hence, the spectral sequence not only characterizes the locus of normal galaxies (except for those whose spectra are dominated for nebular lines) but is almost coincident with their evolutionary tracks. Our results lead us to conclude that *the spectral sequence is also an evolutive sequence, with normal galaxy spectra evolving from late-type irregulars*

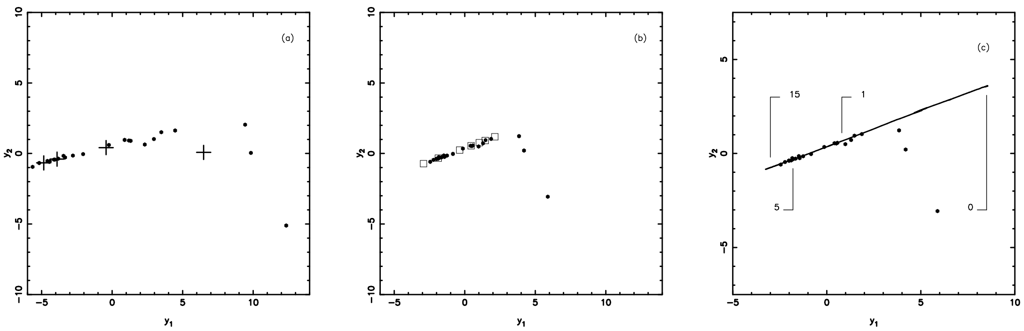

Figure 1. Projection of the spectra of normal galaxies onto the principal plane (dots). a) the projections of the mean spectra of E, S0, Sa-Sbc, and Sc-Im (from left to right) are represented by crosses. b) projection of B&C model spectra for several values of the mean star formation time scale τ and age of 15 Gyr (open squares): from left to right $\tau = 0$, 3, 5, 7, 10, 15 and ∞ Gyr. c) projection of B&C evolutive track for $\tau = 0$, with the age in Gyr indicated next to the track.

to that of ellipticals. Consequently, we expect that the fraction of galaxies with late-type spectra should increase with redshift.

4. The nature of the Hubble sequence

We have seen that there is a close correspondence between the spectral and morphological sequences today, and that the spectral sequence is also an evolutive sequence. If we do not live in a special epoch in the history of the Universe, we may suppose that the spectral and the morphological sequences have been always related. Then the Hubble sequence would be also an evolutionary sequence, with galaxies evolving from Im to E! This is a speculation, of course, since our results refer to spectra and not to morphologies, and then the appearance of an E galaxy with age of 1 Gyr may be quite different of what is today an ∼Sc galaxy. But is worth noting that some recent works present evidence that the morphology of a normal galaxy may evolve from late to early types. For instance, Pfenniger, Combes & Martinet (1994) and Pfenniger, Martinet & Combes (1996) argue that this evolution may be driven by internal and external factors due to the likely coupling between dynamics and star formation, as long as galaxies are able to accrete mass. The key point is that dynamical process that actuate during a galaxy life- like formation and destruction of bars, mergers, close encounters, gas compression and/or stripping, etc.- tend to favour an increase of the spheroidal component at the expense of the disk, leading to a univocal sense of morphological evolution, from Sm to Sa, and eventually to S0 or E.

This sense of evolution also explains the morphological content of galaxy clusters, where most of galaxies are E or S0. The simplest explanation assumes

that there is an infalling population of late-type galaxies (Sodré et al. 1989, Kauffmann 1995) that are transformed in E and S0 (as well as in dwarf ellipticals) in the hostile environment of the clusters. Moore et al. (1996) have recently proposed that frequent encounters at high speed among the galaxies in clusters ("galaxy harassment") may be the driver of morphological transformations in these environments. This process may explain the Butcher-Oemler effect and the form of the blue objects observed in high-redshift clusters by the HST.

Hierarchical models also indicate that galaxy morphology may well change as consequence of mergers and interactions (Baugh, Cole & Frenk 1996), although these models do not have yet enough resolution to address the question of evolution within spiral types.

This scenario also suggests that the first galaxies should look more like faint gas rich irregular objects- in agreement with the inhomogeneous galaxy formation models of Baron & White (1987)- than the presumed bright precursors of today's elliptical galaxies and bulges of spirals in the scenario devised by Eggen, Lynden-Bell & Sandage (1962).

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